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Laboratory and Field Tests of Ultrasonic Sensors for Precision Sprayers

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Abstract. Reliable function of sensors under rough field conditions is required for the development of variable-rate sprayers to deliver pest control agents to tree liners in ornamental nurseries. Two ultrasonic sensors were examined to identify how their durability and detection stability would be influenced by the changes in temperature, wind, dust, travel speed and spray cloud. One of the sensors did not perform satisfactorily under these conditions. The other had a 0.1% variation in root mean square error (RMSE) of the detecting distance before and after exposing to cold weather conditions. Mean RMSE was 8 % under dusty conditions, 1.5–1.8 % under windy conditions, and 12.3 % to 23 % for the travel speed ranging from 0.8 to 3.0 m/s. It also showed that increasing ambient temperature from 16.7 to 41.6 °C reduced the detection distance by 4.0 %. Detecting through spray cloud caused the RMSE to vary from 1.2 to 61.4 %, the largest measurement error among the six variables tested. To reduce the RMSE, optimal configurations between the sensor and spray nozzles were identified. In addition, synchronized multiple-sensor strategies were examined for improving the measurement stability and accuracy of the sensor while detecting targets.

Keywords Variable rate, Nursery sprayer, Real-time sensor, Sensor testing

Introduction

Tree liners are the young trees grown in nurseries to be transplanted at some point in time to fields or containers to become larger, market-ready shade trees. The liners are usually one to three years old, and grow very fast during this time.. For example, red maple, Acer rubrum (*Autumn Blaze)* liners can grow more than one meter during a few months in one growing season (Mathers et al., 2005). The demand for tree liners by the consumers is very strong. The state of Ohio alone annually purchases approximately $14 million worth of liners from other states (Pollock, 2005). Chemical application plays an important role in retaining the quality of tree liners by protecting them from potential biological damages while they are growing. Applicators are expected to continuously adjust the spray volume and targeting as the canopy size changes rapidly during the growing season. Unfortunately many of them are not able to make such changes to optimize pesticide use while attaining satisfactory efficacy from the pesticide applied. They are also not able to stop spraying when there are significant gaps between young trees. A system that automatically adjusts spray volume based on canopy size using sensors is anticipated to achieve both goals: maximum efficiency and efficacy. by applying the desired amounts of spray to target trees.

Measuring canopy size is a challenge due to complicated structures and irregular shapes of trees. Various remote sensing techniques have been investigated to achieve this goal. For example, light interception and aerial stereoscopic imaging techniques have been adapted to estimate tree canopy size (Meron et al. 2000). Satellite images have also been used to estimate canopy volume of trees in forest (Mäkelä and Pekkarinen, 2004; Carreiras et al., 2006; Mõttus et al., 2006; Le Maire et al., 2008).

However, the scale of these remote sensing techniques is relatively large, consequently, the sensing resolution may be insufficient for a real-time variable rate application in the nursery field. In addition, remote sensing techniques typically have a chronological gap between detection and application, resulting in application errors. To diminish this problem, the LIDAR (Light Detection and Ranging) system or laser scanner has been used to measure the canopy volume and showed a promising results that the measured canopy volume close to manually measured volume (Wei and Salyani, 2005; Lee and Ehsani, 2008; Polo et al., 2009). Unfortunately, limited row spacing in the liner field may restrict LIDAR to be used in variable rate liner sprayers. It is also a relatively expensive sensor ($2,000 – $5,000). Furthermore, since a typical tree liner sprayer treats more than one row at a time, each liner row requires an individual LIDAR system to take the tree canopy variation of each row into account for variable-rate application. This will further raise the application cost to an unpractical level.

Ultrasonic ranging technique sensors that are affordable and relatively robust against outdoor conditions capable of estimating the canopy volume of trees satisfactorily were developed by several researchers (Giles et al., 1988; Tumbo et al., 2002; Zaman and Salyani, 2004). These studies, however, were focused on sensing canopy volume of fully grown trees with relatively large intra-row spacing as a sensing distance. In addition, while ultrasonic sensors have been used in earlier studies for detecting canopy size, sensor performance has not been well examined under field application conditions. Furthermore, liner field application presents unique challenges to a canopy sensing system, i.e. relatively dense liner planting arrangement, fast changes in canopy size and color, and limited working space between rows for the sensing system. Ultrasonic sensors may enable to overcome these challenges due to their small size, robust sensing mechanism against color variation in targets, and uni-directional sensing sight.

However, questions are still remains whether ultrasonic sensors can be integrated into field sprayers for the relatively narrow-row liner nursery application. A wide range of operational parameters were selected in this study to examine the sensor performance for field applications. These parameters included air-temperature, wind velocity, presence of dust, air temperature and spray cloud conditions.

The overall objective of this research was to verify feasibility of an ultrasonic sensing system used for variable rate spraying. The specific objectives are:

1) testing durability and measurement stability of an ultrasonic sensor under potential spray application conditions; and

2) determining the optimum sensor implementation strategy and testing multiple sensors for a variable rate sprayer for sensing the volume of artificial targets.

Materials and methods

Ultrasound Sensor

An indoor-use, ultrasound sensor (LV-MaxSonar-EZ4, Maxbotix Inc, Brainerd, MN, USA) was initially selected for this study. However, the sensor failed to detect objects when spray droplets settled on the transducer due to the ultrasound speed change between droplet water and air. In addition, the sensor circuitry was vulnerable to spray drift because its circuitry was unprotected. Consequently, the detection accuracy of the sensor was unstable. This lead us to look for a water-proof sensor with a protective enclosure. An water and dust ingress protected ultrasound sensor (LV-MaxSonar–WR1, Maxbotix Inc, Brainerd. MN, USA) was identified and utilized in these studies. The sensor was rated as IP 67 which refers dust tight (6) and 1-m water immersion protection (7), (CENELEC, 2000). The sensing resolution is 3.82 mV/cm with an approximate beam angle of 10 degrees. The sensor body was constructed with a pipe connector and cable grip to protect the sensor in the outdoor conditions (Figure 1).

Data Acquisition System

To acquire data from sensors, a custom–design data acquisition system was built with a peripheral interface controller (PIC) (PIC18F4523, Microchip technology Inc., Chandler, AZ, USA). The microcontroller triggers the sensor and receives analog signals from the sensor. Then, by using its embedded 12-bit analog-to-digital (AD) converter module of the controller, the signal is converted to a digit, a discrete number ranging from 1 to 4096. The system resolution of the data acquisition and sensor in measuring distance was 0.32 cm. After the AD conversion, the digital information is sent to a laptop computer via a serial communication. A user interface using Visual Basic.NET (Microsoft Co. LTD, Richmond, WA, USA) was written to examine sensing results and to save data in a text file at various sampling rates.

Ultrasonic Sensor Testing under Potential Field Spray Application Conditions

Durability is one of the major factors for the quality of sprayers, thus, the sensor attached to the sprayer must be tested under potential outdoor application conditions to determine if they can be satisfactorily implemented on variable-rate sprayers. For this study, the conditions were selected based on the possibility that the sensor might encounter during spray and non-spray seasons. The sensor was evaluated under following six conditions: outdoor cold weather, wind, dust, travel speed, air temperature, and spray cloud. The six conditions were selected because they were essential factors that the sensor must overcome to be successfully used under various field application conditions .

Cold Temperature Exposure

To evaluate the sensor performances and durability after exposure to cold weather conditions, the IP67 sensor was mounted on a weather station for 40 days between March 4 and April 13, 2009. The ambient temperature and precipitation were recorded by the weather station and illustrated in Figure 2. The root mean square (RMS) errors of the detecting distance for a 46-cm artificial plant was evaluated before and after the sensor was exposed outside conditions for 40 days. The differences in RMS errors of the IP67 sensor after the exposure to cold temperatures were subjected to Analysis of Variance (ANOVA) with MS-Excel software (Microsoft Co. LTD, Redmond, WA, USA).

Wind Test

A wind tunnel was used to evaluate the sensor accuracy and measurement stability under windy conditions. The tunnel simulated laminar wind flow at different speeds passing through the sensor detecting area.

The IP67 sensor was perpendicularly mounted to airflow at 73.4 cm above the tunnel floor to measure the distance to the tunnel floor. An air velocity meter (Model 8386A, TSI Inc., Shoreview, MN, USA) was used to measure the wind speed (Figure 3) approximately 66 cm downstream from the sensor. The range of tested wind speeds was from 1.5 to 7.5 m/s with 1.5 m/s increments. This range represented conditions that can be defined ideal to caution advised spray conditions (Deveau, 2009). The ultrasonic sensor output data was acquired for 5 minutes at sampling rate of 10 Hz with 3 replications for each wind speed. The impact of wind in RMS errors of the IP67 sensor were examined by ANOVA.

Dust Cloud Test

The RMS error of the sensor was determined under the simulated dust condition to evaluate the sensor performance. The sensor was mounted at the top of a box (74.0 cm (W) × 62.9 cm (L)× 95.3 cm (H)), and a funnel to discharge dusts over sensing area was placed 17.8 cm away from the sensor (Figure 4). The distance between the sensor and the ground was detected by the sensor. Dusts were created by gradually pouring 570 g of 234-micron screened ground soil via the funnel for 50 seconds. A fan was used to blow the air at a velocity of 3.6 m/s into the box and carry the dust particles through the detection area. The sensor output was collected for 50 seconds and synchronized with dust discharge time at the sampling rate of 10 Hz with three replications.

Travel Speed

The sensor was evaluated for its detection accuracy and measurement stability in RMS error at various travel speeds. A custom-designed linear track was used to simulate sprayer travel (Figure 5). The sensor was mounted on the track and driven by a stepper motor. The sensor targets were 40-cm high and 106.7-cm long artificial plants, placed 81.9 cm under the track.

The sensor travel speed ranged from 0.76 m/s to 3.24 m/s, measured with a radar gun (Railmaster-VP, Decatur Electronics Inc., Decatur, IL, USA). The detection data provided by the sensors were categorized into five travel speed groups: 0.76 – 0.93 m/s, 1.33 – 1.60 m/s, 1.78 – 2.13 m/s, 2.36 – 2.67 m/s and 2.71 – 3.24 m/s in corresponding to the average speed of 0.8, 1.5, 2.0, 2.5 and 3.0 m/s, respectively. While the sensor was travelling, the data acquisition system collected the target distances for 5 seconds at the sampling rate of 20 Hz. Attempts of detecting targets from eight to ten times were made for each speed group.

Air Temperature

An insulated chamber (0.91 cm wide(W),× 0.91 cm long(L) × 1.22 cm high(H)) with 2.5 cm thickness-foam was built to maintain relatively steady and uniform temperature for testing the influences of air temperature on detection results. The chamber temperature was controlled by discharging heated air into the chamber. The ultrasonic sensor was mounted at the top center of the chamber with the height of 125 cm from the base. The inside temperature of the chamber was measured at three positions using T-type thermocouples. The thermocouples were installed at the side of the chamber at heights of 2.5, 70 and 113 cm from the base. The temperature and distance between the sensor and the base were measured continuously with a data logger (CR3000, Campbell Scientific Inc., Logan, UT, USA) at the sampling rate of 1 Hz.

To classify sensing data with relatively homogeneous chamber air temperatures, sensing data with a chamber temperature variation greater than ± 1 °C from the average temperature was eliminated. The range of average air temperatures in the chamber for the test was from 16.7 to 41.6 °C after the elimination.

Spray cloud

The sensor RMS error was examined under spray clouds discharged from a spray nozzle (XR11003, Teejet Co., Wheaton, IL, USA). The sensor was mounted at the top of an upside-down 2.13 m × 2 m L-shape frame (Figure 6). To develop a sensor implementation strategy with a spray nozzle with minimum influences on detection stability and accuracy of the sensor, configurations of horizontal distance (HD), vertical distance (VD), and longitudinal distance (LD) between the sensor and the nozzle (sensor-nozzle configuration) were arranged on the test frame (Table 1).

For each sensor-nozzle configuration, the nozzle discharged spray clouds via an air pressurized chamber perpendicularly to the detecting area of the sensor. The nozzle was operated at the following pressures: 207, 276. 345 and 414 kPa. Each pressure setting was carefully adjusted by controlling air pressure to a water chamber. Spray nozzle operation was controlled by a solenoid valve (Capstan Ag Systems, Inc., Topeka, KS, USA) coupling with an N-channel power MOSFET (Metal–Oxide–Semiconductor Field-Effect Transistor, RFP12N10L, Fairchild, South Portland, Maine, USA) to form a solid state relay (SSR). The microcontroller in the data acquisition system triggered the SSR via a logic signal to synchronize between the data acquisition and nozzle spraying.

While the nozzle was spraying water through detection area of the sensor, the sensor continuously measured the distance to a 46-cm tall artificial plant for each sensor–nozzle configuration. Data were collected for 5 minutes at the sampling rate of 10 Hz with 3 replications for each sensor–nozzle configuration. Measurement stability of the sensor was represented in RMS error between detected and actual distances.

Multiple Sensor Operation

Five ultrasonic sensors were vertically mounted on a 2.1 m bar with a sensor spacing of 0.30 m to identify interference issues between sensors and to examine the accuracy in detecting canopy volume. Five sensors were controlled and synchronized by a custom designed microcontroller to simultaneously detect targets in each position. Detection results were acquired by a computer via RS-232, and the acquired data was stored in a text file.

Interference between sensors was noticed during the preliminary experiment due to changes in sound wave direction by angled surfaces. An interference prevention shell was designed and mounted on the sensor’s enclosure (Figure 7) to isolate the pathway for ultrasonic wave of IP67 sensors and to prevent the interference between sensors while sensing angled surfaces. The shell diameter was approximately 7.62 cm, and the cover extends approximately 11.43 cm from the transducer. A sound absorbing form with a thickness of 2.54 cm was glued around the inside shell, thus approximately 2.54-cm diameter circle opening was available to transmit and receive the sound wave.

Two experiments were carried out to test synchronized multiple sensor operation and its detection accuracy. A flat wood panel (185.4 cm (H) × 24.8 cm (W)) was placed at specific distances (30.5, 38.1, 45.7, 53.3, 61.0 and 68.6 cm) from the sensors to examine detecting accuracy. In addition, artificial canopies with elliptical, diamond and diagonal shapes were created to test the sensors. Target detection results of the sensors through the experiments were collected with three replications, and RMS errors of the sensing results were computed to evaluate the detection accuracy.

Results and discussion

Cold Temperature Exposure

There was no change in function or accuracy of the ultrasonic sensor after it was exposed to outdoor cold temperature conditions for 40 days. RMS error of the measurements ranged from 2.15 to 4.06 cm with the mean of 3.31 cm and 2.71 to 4.94 cm with the mean of 3.55 cm for before and after the exposure, respectively (Table 2). The increase of mean RMS error was 7.3 % after the exposure; however, the result of ANOVA indicated that the increase was insignificant ($P = 0.81$). This insignificant difference in the RMS errors implies that the enclosure of the sensor provides sufficient durability and performance under outdoor conditions.

Wind Test

The RMS error of the sensor ranged from 1.11 to 1.34 cm (Table 3) across all wind speed conditions evaluated. No significant difference between RMS errors within the wind velocity range from 1.5 to 7.5 m/s was found ($P = 0.11$) from ANOVA. This indicates that the accuracy and function of the sensor were not influenced by the tested wind speed range. Thus, the measurement stability of the sensor was reasonable under windy conditions.

Dust Cloud Test

Results of measurements taken to determine the stability of sensors under dusty condition revealed that the sensor had sufficient detection stability under dusty conditions although the transducer of the sensor and sensing area were covered by dusts. The RMS error ranged from 4.99 (6.4 % of sensing distance) to 8.46 cm (10.9 %) with the mean of 6.2 cm (8.0 %) for the target 77.5-cm away from the sensor. Therefore, the sensor had reasonably sufficient measurement stability and accuracy under dusty conditions exceeding those that would be observed during field applications.

Travel Speed

Mean RMS errors of the sensor ranged from 10.1 to 19.4 cm while detecting targets 81.9-cm away from the sensor at average traveling speeds of 0.8 to 3.0 m/s (Table 4). Relatively large mean RMS error (19.4 cm) was observed at the low speed (0.8 m/s). The lowest mean RMS error (10.1 cm) occurred at the 2.0 m/s travel speed.

In our test, the sensor generally showed acceptable performances for detecting the targets within the travel speeds tested. Random detecting error was observed during the test because of variations in leaf orientations and canopy densities of artificial plant. Zaman and Salyani (2004) also reported that sensing variation along the traveling speeds might be caused from target scanning frequency and canopy variability. Our sensing error might have resulted from the acoustic wave bouncing between angled leaves until the wave returned to the sensor's receiver (multi-return path effects) due to leaf orientations (McKerrow and Neil, 2001).

However, because of the error frequency (1.0–5.6 % of collected data) and abnormal noise amplitude, a filtering process using derivative between two sensing points might increase the detecting accuracy by eliminating the error. In evaluating this hypothesis, results of the further tests we conducted indicated the range of RMS errors was reduced from between 10.1 (8.3 % of detecting distance) and 19.4 cm (15.9 %) to between 6.4 (5.2 %) to 7.9 cm (6.5 %) by using the filtering technique for the travel speed range from 0.8 to 3.0 m/s.

Air Temperatures

Within the air temperature range from 16.7 to 41.6 °C, two distinctive changes in detection distances were identified as the chamber temperature increased: a change in detection distances occurred between the air temperatures of 18 and 19 °C, and the other change occurred as the air temperature increased from 34 to 35 °C. The average detection distance decreased by approximately 2.5 cm (2 % of the sensing distance of 125 cm) for each change. The sensor showed 0.5 cm , 2.2 cm and 4.6 cm (0.4 %, 1.8 % and 3.7 % of the detecting distance of 125 cm, respectively) of RMS errors from the actual distance when the air temperature was below 19 °C, between 19 to 35 °C and above 35 °C, respectively. The potential maximum change in average sensing distance due to the air temperature increased from 16.7 to 41.6 °C was 5.0 cm (4 % of the sensing distance).

The change in the speed of sound between two air temperatures can be described in a square root of a ratio of two temperatures in kelvin (Bohn, 1988). Results of tests we conducted revealed that the average detection decreased by 4 % while the potential sound speed increased by 4.21 % for the temperature range tested (19 to 35 °C). A disagreement of approximately 0.21 % was observed between the actual measured sensing result decrease and the sound speed increase. The disagreement could be explained from data sampling method which allowed for ± 1°C temperature variations in chamber air temperature from average temperature.

Spray Clouds

The IP67 sensor had a wide range of mean RMS errors from 2.3 cm to 83.0 cm under spray clouds when the detection distance was 167.6 cm (Table 6). It was noted that vertical distance (VD), horizontal distance (HD), and longitudinal distance (LD) configurations between the sensor and nozzle influenced in the measurement accuracy. For instance, increasing VD reduced RMS errors because the transducer of the sensor was beyond the spray cloud area, thus, condensation on the transducer was avoided.

On the other hand, when HD increased to 0.6 m from 0.3 m, the RMS error showed a relatively small decrease because the increase in HD did not prevent droplets from settling on the transducer although increasing HD affected droplet trajectories and travel distances to the transducer. However, increasing LD improved the measurement accuracy of the sensor because the spray cloud was outside the detection range of the sensor.

In general, increasing VD and LD improved the detection accuracy. This experience led to the development of a key strategy to improve detection accuracy of the ultrasonic sensor. The strategy is to prevent spray droplets from settling on the transducer to increase the detection accuracy because water on the transducer influenced the sensor accuracy by changing travel speed of sound.

With a mean RMS error from a sensor-nozzle configurations using the newly identified detection strategy (mean RMS error: 4.2 cm (HD: 0.31 m) and 4.5 cm (HD: 0.61 m); VD: 0.61 m and LD: 0.30 m), variations in the canopy size sensing results and their influence in application rate could be estimated. For example, the RMS errors from the detection strategy might result in over application of 26.8 µL to 92.0 µL of material per a nozzle for a regular sensing interval of 50 ms and sensor spacing of 0.3048 m. Following assumptions were used to estimate spray variation: Sensing frequency of 20 Hz, trapezoid canopy shape within sensing area, travel speed range of 0.45 to 1.34 m/s and an application rate of 93.8 mL/m^3 (Anonymous, 2009) were used. The variation in spray delivery resulting from inaccurate target detection might range from 5.3 to 7.9 % for each sensing cycle, thus, the reasonable detection accuracy for nursery spray application could be achieved from the sensor.

Multiple Sensor Operation

The IP67 sensors showed reasonable accuracy with RMS error ranging from 0.26 to 6.91 cm (Table 7) while detecting the wood panel target. For three irregular shapes, RMS error range of detection results were from 4.18 to 12.77 cm.

During the test, the sensors continuously underestimated the target distances (Figure 8) because relatively high air temperature (29 °C) influences the sound speed as we experienced in air temperature tests. This underestimation might cause overestimation of canopy volume (Giles et al., 1988). Inaccurate detection of canopy volume would cause targets to be over or under sprayed. For example, these results showed that the IP67 sensing system we tested might cause spray rate variation from 9.3 to 135 % of desired application rates (based on following parameters: regular sensing interval of 50 ms, travel speed from 0.45 to 1.34 m/s, maximum canopy distance of 60.96 cm and application rate of 93.8 mL/m^3). It should be noted that the maximum variation occurred when the target volume was relatively small (16.3 % of the maximum volume). The variation in the application rate could be reduced to 0.2 – 35 % of desired application rates after pre-calibration. Thus, a pre-calibration process to identify and compensate the potential sensing offset by air temperature variations is recommended to improve the sensor accuracy.

Summary and Conclusions

Durability and measurement stability of an ultrasonic sensor were investigated under simulated field conditions for the development of variable rate nursery sprayers. In addition, potential issues in detecting a target with multiple synchronized sensors were investigated by integrating them into a prototype sprayer system operated under typical field application conditions. Although the sensor showed an inherent issue in the accuracy due to its sensing mechanism when the transducer was wet, the error could be minimized by optimizing the sensor and nozzle configuration strategy. Specific conclusions from this study are as follows:

1) The outdoor winter conditions did not significantly change the function and accuracy of the ultrasonic sensor. The mean RMS error of detection distances was increased by 7 % (from 3.31 cm to 3.55 cm) after the 40-day outdoor exposure; however, the increase was not significant.

2) The sensor operated steadily under the windy and dusty conditions with the mean RMS errors of 1.25 cm and 6.18 cm, respectively.
3) Mean RMS of the sensor ranged from 10.1 to 19.4 cm when artificial plant targets were 81.9-cm away and the travel speed ranged from 0.8 to 3.0 m/s. Utilizing a filtering process to avoid noise improved the measurement accuracy by reducing RMS errors to 6.4 – 10.1 cm.
4) The accuracy of the sensor was not affected by temperature when air temperature was below 19 °C. The mean RMS error increased to 2.2 cm at the temperature from 19 to 35 °C, and 4.6 cm at the temperature above 35 °C. This result demonstrated the sensor had sufficient accuracy within the ambient temperature range (19 – 35 °C) for the field sprayers operation by achieving a low mean RMS error.
5) The RMS error ranged from 2.00 to 102.90 cm under spray cloud conditions when the artificial plant was 167.6 cm away from the sensor. The key to improve the accuracy of the ultrasonic sensor under spray cloud conditions was to avoid condensation on the sensor transducer.
6) Isolating the pathway for ultrasonic wave of the sensor was desirable to avoid interference between sensors when synchronized multiple ultrasonic sensors were operated.

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Table 1. Sensor-nozzle configurations for the test

Configuration	Distance (m)
Horizontal distance (HD)	0.30 and 0.61
Longitudinal distance (LD)	0*, 0.15, 0.3, 0.45 and 0.61
Vertical distance (VD)	0.3, 0.61, 0.91 and 1.22

*0 means the sensor and nozzle were placed in longitudinally equal line.

Table 2. RMS errors of the sensor detecting distances before and after 40-day exposure under outdoor winter conditions

	Before exposure	After exposure
RMS error (cm)*	2.15	2.71
	4.06	3.00
	3.72	4.94
RMS error mean (cm)	3.31	3.55
SD**	1.02	1.21

*RMS error: Root mean square error between actual and detected distances

** SD: Standard deviation

Table 3. RMS error of the sensor detecting distances under various wind speed conditions

	Wind speed (m/s)				
	1.5	3.0	4.5	6.0	7.5
RMS error* (cm)	1.27	1.34	1.16	1.16	1.11
	1.27	1.32	1.17	1.19	1.41
	1.30	1.30	1.22	1.16	1.37
RMS mean	1.28	1.32	1.18	1.17	1.30
SD**	0.02	0.02	0.03	0.02	0.2

*RMS error: Root mean square error between actual and measured distances

** SD: Standard deviation of the RMS errors.

Table 4. Mean RMS for the 121.92 cm detection distance under various travel speed conditions

Average speed (m/s)	0.8	1.5	2.0	2.5	3.0
Mean RMS error (cm)*	19.4	12.7	10.1	12.32	10.8
SD**	11.2	14.3	13.3	13.4	8.0
Sensing error (%)	5.0	1.6	1.0	3.2	5.6

*RMS error: Root mean square error between actual and sensing distances.

** SD: Standard deviation of the RMS errors.

Table 5. Detected distances of targets 125 cm away from the sensor under the ambient temperature ranging from 16.7 to 41.6 °C

Air temperature range (°C)	Below 19	19 to 35	Above 35
Average detected distance (cm)	125.32	122.83	120.36
Coefficient of variation (%)	0.34	0.22	0.17
Measurement change (%)	–	– 2 %	– 4 %
RMS error (cm)	0.5 (0.4 %)*	2.2 (1.8 %)	4.6 (3.7 %)

* Figures in parenthesis are percentage of RMS error to the 125 cm target distance

Table 6. Means of RMS errors (cm) collected from the sensor and nozzle configurations with nozzle operating pressures range from 207 to 414 kPa

Vertical distance* (m)	Horizontal distance* (m)		Longitudinal distance* (m) 0	0.15	0.30	0.45	0.61
0.30	0.30	Max.	119.4	74.7	10.3	9.2	9.1
		Min.	42.61	2.0	1.4	2.5	3.4
		Mean	83.0	12.1	5.3	4.7	6.6
		SD**	26.6	12.7	1.0	2.2	1.7
	0.61	Max.	85.4	80.2	9.5	8.3	8.0
		Min.	10.3	6.9	2.5	0.6	2.3
		Mean	27.9	14.1	5.1	4.2	4.2
		SD	11.4	17.3	2.8	3.0	3.1
0.61	0.30	Max.	101.6	30.0	**9.0**	8.6	**8.8**
		Min.	32.2	2.4	**1.1**	2.2	**1.4**
		Mean	77.0	7.3	**4.2**	6.2	**4.5**
		SD	10.5	4.4	**1.5**	1.9	**2.4**
	0.61	Max.	64.6	51.6	**7.4**	7.1	**9.5**
		Min.	3.0	4.3	**2.3**	0.0	**2.2**
		Mean	12.0	11.3	**4.5**	4.1	**3.2**
		SD	11.5	8.8	**2.5**	2.6	**2.7**
0.91	0.30	Max.	12.1	9.0	10.4	**8.9**	8.4
		Min.	2.1	3.5	1.6	**0.0**	1.8
		Mean	6.1	6.8	5.5	**4.8**	5.2
		SD	0.7	1.7	2.2	**2.9**	2.1
	0.61	Max.	37.6	41.0	8.0	**8.1**	8.7
		Min.	3.8	2.6	2.9	**0.7**	2.5
		Mean	10.4	13.4	4.5	**3.9**	4.5
		SD	6.6	10.6	1.9	**2.2**	3.0
1.22	0.30	Max.	12.3	8.9	9.4	9.5	8.1
		Min.	2.1	2.5	1.8	0.0	2.2
		Mean	8.2	5.6	5.5	6.0	4.4
		SD	2.4	0.7	1.3	2.6	1.0
	0.61	Max.	6.5	12.6	6.2	10.3	10.0
		Min.	1.4	4.4	1.3	0.0	1.17
		Mean	3.1	6.5	2.3	3.6	3.3
		SD	1.9	4.4	1.4	2.6	1.8

*Distance is between the sensor and nozzle
** SD: Standard deviation of the RMS errors.

Table 7. Mean RMS errors (cm) of vertically installed five sensors while detecting targets at 30.5, 38.1, 45.7, 53.3, 61.0 and 68.6 cm away from the sensors

Target Detecting Distance (cm)	Sensor 1*	Sensor 2	Sensor 3	Sensor 4	Sensor 5
30.5	0.26	0.31	0.27	0.35	0.35
38.1	4.40	4.84	4.80	4.30	4.87
45.7	5.03	6.13	5.03	5.01	5.00
53.3	4.64	2.48	2.54	4.58	4.92
61.0	5.02	4.88	6.91	6.28	5.01
68.6	4.66	4.78	6.74	4.69	4.96

*Sensor 1 was mounted approximately 30.5 cm above from the ground and the spacing between sensors was 30.5 cm.

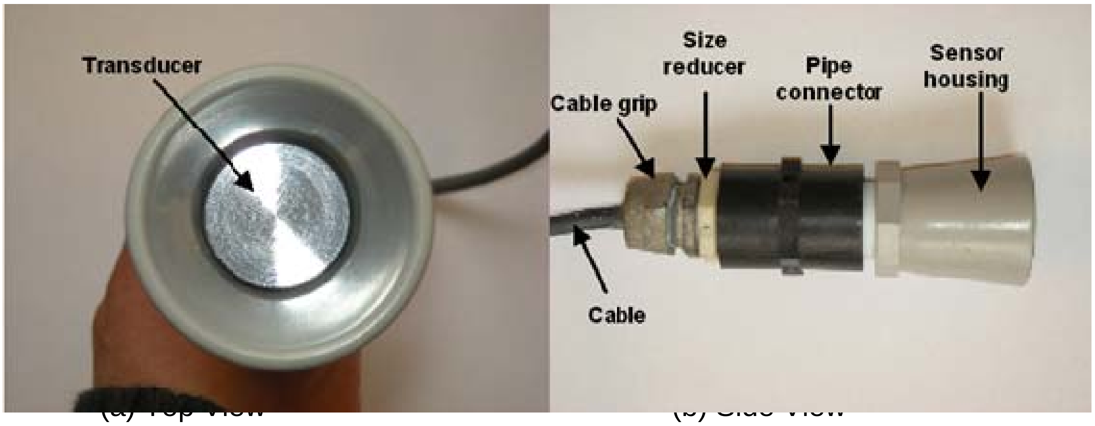


Figure 1. Ultrasonic sensor with protection components for outdoor conditions

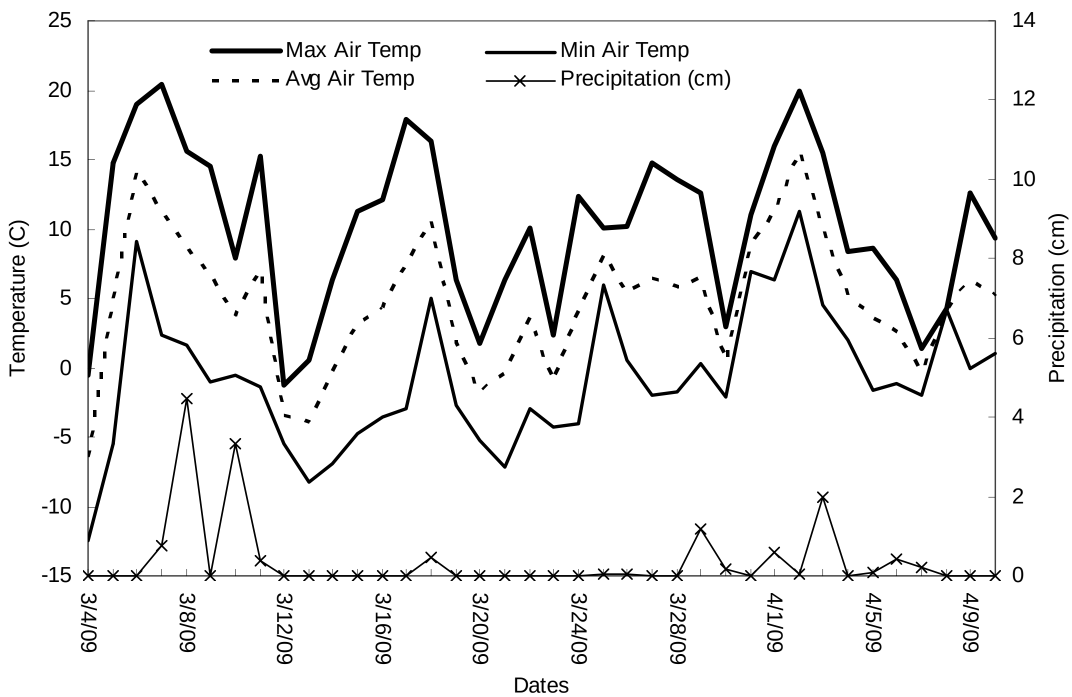


Figure 2. Ambient temperature and precipitation during the outdoor winter durability test of the sensor

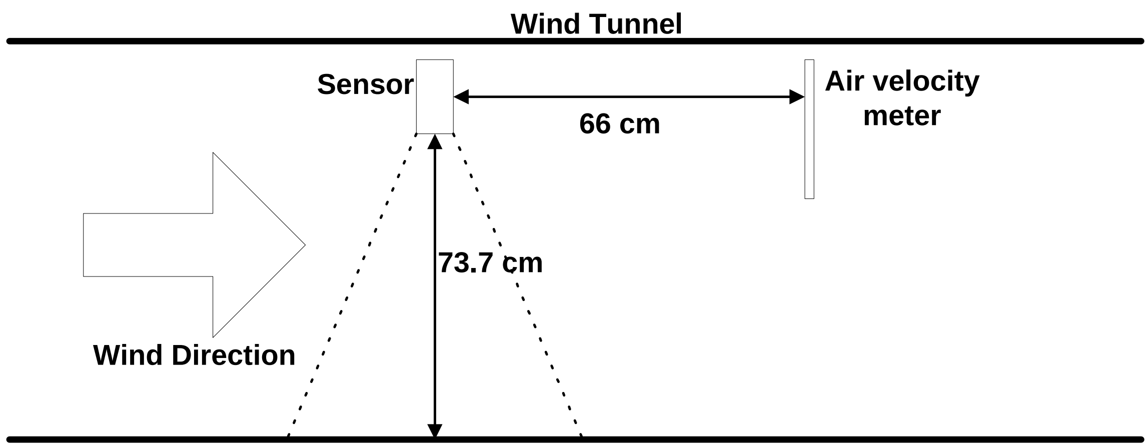


Figure 3. Wind tunnel setup for the sensor stability test under windy conditions

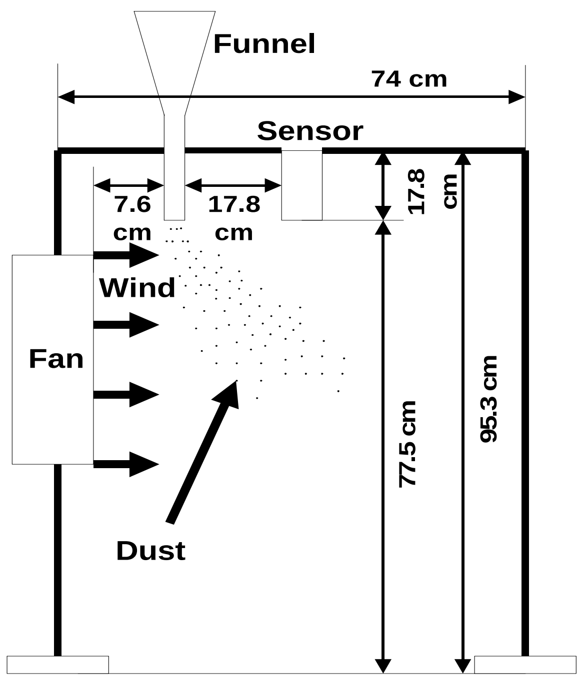


Figure 4. Experimental setup for the sensor stability test under dust conditions

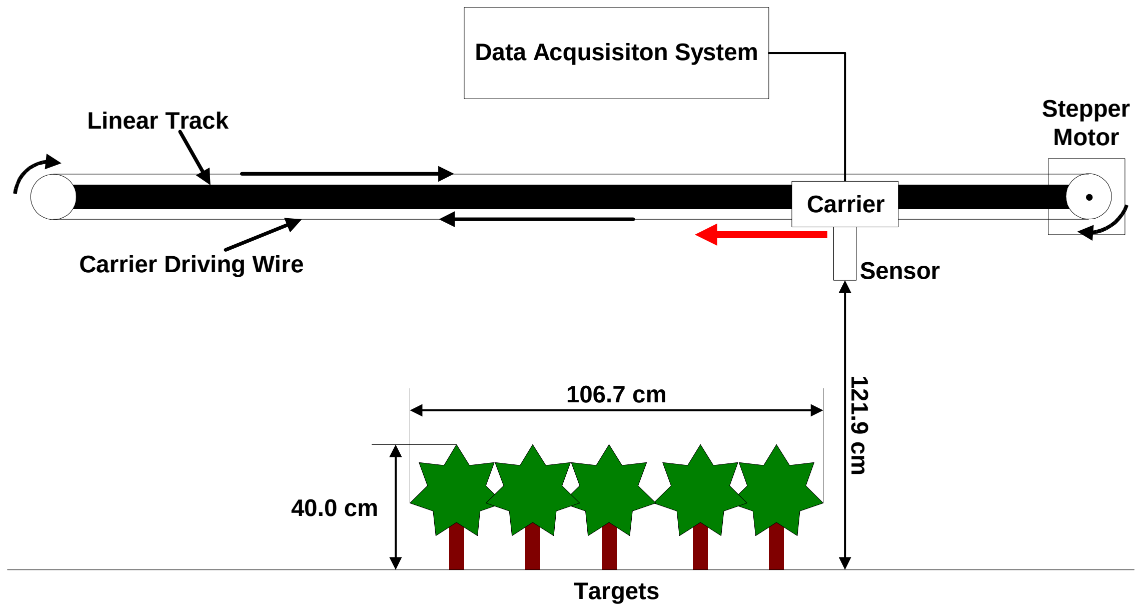


Figure 5. Experimental setup to test the sensor stability at various travel speeds.

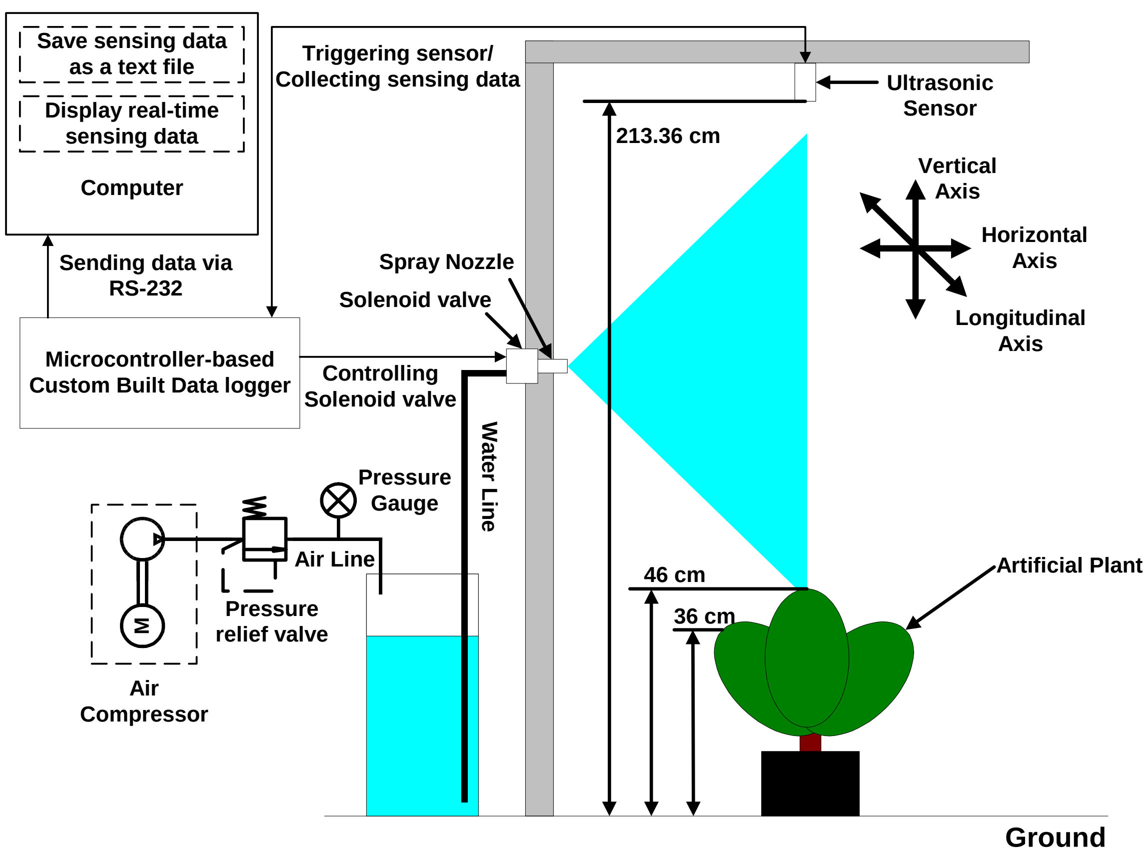
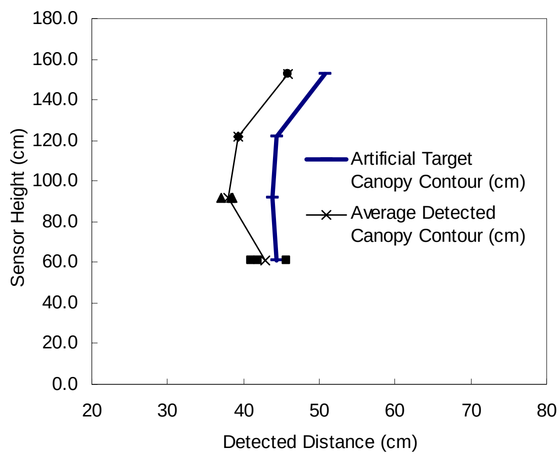
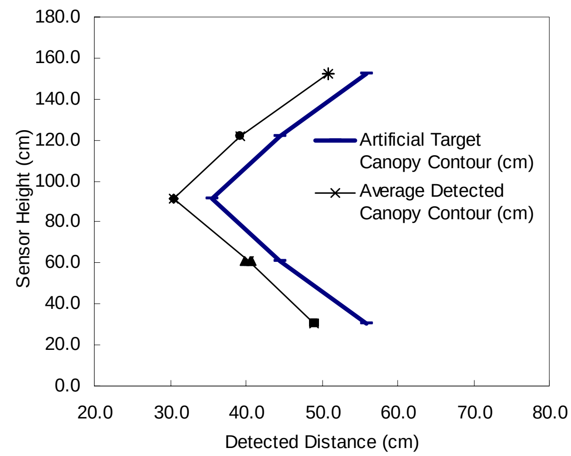


Figure 6. Experiment setup to test the sensor stability with the spray clouds

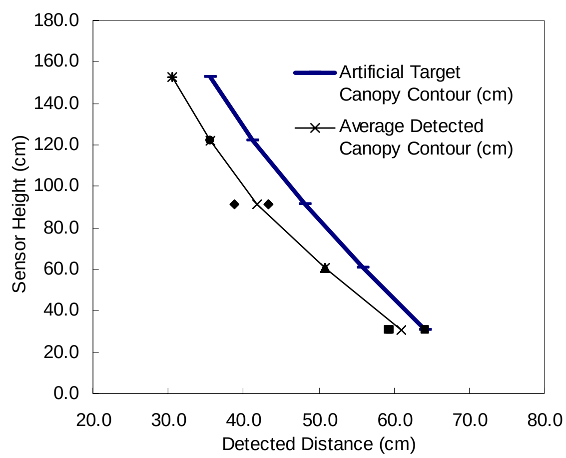
Figure 7. Ultrasonic sensor with an interference prevention shell



(a) Ellipse shape



(b) Diamond shape



(c) Diagonal shape

Figure 8. Detecting results of artificial canopy shapes by vertically installed sensors